International Journal of Modern Developments in Engineering and Science
Volume 3, Issue 10, October 2024
https://www.ijmdes.com | ISSN (Online): 2583-3138

Transient Analysis in the Networked Control System with Compensator Design

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***Abstract*: The transient performance and stability of networked control systems (NCS) must be maintained, as the introduction of uncertain parameters deteriorates system performance and causes instability. Therefore, the main objective of this paper is to analyse the performance of NCS systems under uncertain conditions, like disturbances. Different compensator design are presented and a few suitable stability conditions are used to illustrate NCS's performance. The effectiveness of the suggested methodology is demonstrated by the simulation diagram in the results section, which also includes a comparison of the response signal with different compensator design and NCS disturbance. Experiment is carried out within the MATLAB Simulink environment to show how effectiveness of the recommended method.**

***Keywords*: Networked Control System, Packet Loss, Delay, Proportional Integral Control, Denial of Service, Attacks.**

1. Introduction

It is expressed that as technology advances quickly, the transfer of information through communication networks has grown in significance. The review of the literature shows that when collecting information by breaking into a network, hackers exercise caution. Using the provided information, an attacker can design and carry out an attack on an NCS to lower control performance. Many instances of attacks, such as the cyber grid attack, the Stuxnet worm, the Maroochy water attack, and the cyber-attack on the German Steel Mill, have been documented in the literature [1], [2]. In order to immediately adjust closed-loop performance in response to network signals, the author suggested a networked-predictive policy. The prerequisites for stability were also discussed; these depend on latency and transmitting data loss for the closed-loop NCS [3]-[5]. Paper [3] investigates the NCS stabilization problem with random packet losses. Stability analysis demonstrates that the proposed method's multi-objective system with uncertainty bound more closely approximates the discrete time system. By removing exogenous dynamics that deteriorate performance, the author discussed the constrained optimal-switching control problem with an industrial NCS. To identify malicious activity on the part of Industrial NCS, a random distribution procedure was used to represent the attack order in the process. Furthermore, to model delay, the Bernoulli distribution process is utilized [6], [7].

The control performance improvement plan for the NCS that was disrupted during a denial-of-service attack is observed. An event-triggered predictive control methodology is also presented to counter denial-of-service attacks. Considering the disturbance model, a controller confirming that the system states converged to a different invariant set is evaluated. The author also discussed the stability requirements that must be met in order to guarantee that the closed loop NCS system is uniformly and conclusively bound [8].

The main contribution of this paper is an analysis of the impact of disturbances and uncertainty on networked control systems. Different compensator design are presented and a few suitable stability conditions are used to illustrate NCS's performance.

The sections of this paper are organized as follows: The thorough literature review that was conducted to determine the problem is included in section 2. Section 3 defines the problem formulation and mathematical expression. The simulation's results are displayed in Section 4. Section 5 offers evidence in favor of the final judgment and further research.

2. Literature Review Work

Stability conditions and improved control schemes were presented in order to lessen the effects and stop the intended data from being obtrusive. The Kalman-filter, Linear Gaussian Control, and PID controller were developed to lessen the impact of attacks and deliberate disruptions on the NCS. The design accurately approximates the system and measurement states in the face of uncertainty. In addition, the author employed optimization algorithms to optimize coefficients and compute system identification parameters, which were subsequently used to model the planned attack aimed at compromising the system [9], [10]. Furthermore, certain control law conditions were provided in [11]-[14] to improve the performance of the closed loop networked system.

The co-design stabilization control framework, which was demonstrated for NCS under DoS attack. It also reveals that the state is periodically measured and that the controller updates the data using an event-based triggering strategy. The gain was computed for a specific sampling rate and dynamic event triggering. It has been reported that performance against DoS has improved and control updates have decreased [15], [16]. Networked-connected control systems (NCCS) were given a predictive control to mitigate the effects of malicious attacks

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and network imperfections. According to [17], [18], the adopted methodology improved system transient performance and stability for a range of packet loss values.

The white sequence of the Bernoulli distribution was used to model a number of network imperfections, including packet loss and delay. Next, the impact of these parameters on NCS was investigated. Some suitable stability conditions involving linear matrix inequalities and Lyapunov stability were stated [19]-[21] in order to illustrate the effectiveness of the method. Furthermore, the advantages of optimal control design were examined in [22] for industrial networked control systems (iNCS) in addition to uncertainty parameters like packet loss and network delay. The improved iNCS transient performance was demonstrated by this design. The efficacy was evaluated under various network latency and packet loss rates. This paper's author focused on the mean square stabilization problem that arises in NCS because of the channel's long fading length. Additionally, the stability condition was presented by the author using the algebraic Riccati equation [23], [24].

In [25]-[27], the influence of instabilities terms on NCS is investigated, and it is demonstrated that attacks can be announced in a forward or backward direction via a communication channel. In addition to these intentional attacks, the effect of process and measurement noise on the system performance of the networked control system is investigated with the use of the Kalman Filter (KF) and suitable stability conditions. The event-triggered scheme intended for channel sharing is used to evaluate the continuous-time NCS using induced delay and packet loss. The performance parameter and controller are analyzed using event-triggered and Lyapunov functions, demonstrating the effectiveness of the method that has been proposed [28]. Further evaluations of the effects of packet loss in networked systems can be found in [29]-[31].

The Bernoulli distribution process employed to analyze the packet loss and time delay problem in NCS. Network control systems perform better when state feedback control design is included, as demonstrated by the exponential stability condition [32]-[34]. The network effects of packet loss and random delay for the nonlinear stabilization NCS problem were discussed in this article. The T-S fuzzy model was introduced to simulate a fuzzy switched system with an unknown dynamic parameter. The exponential stability was presented using a methodology of slow and fast switching dwell times [35]-[37]. Furthermore, an observer-based stability problem for NCS was investigated. This problem involved packet loss and time delay in both directions, from sensor to controller and vice versa. The author also computes the gain matrix of the stabilized closed loop system.

The discrete-time proportional derivative controller is analyzed in the presence of packet loss and random network delay using a backward difference equation. In the True-Time simulator, packet loss occurred during the planned controlled NCS's effectiveness. The findings showed that the battery consumes more energy when a packet is lost [38]-[40]. The author described a neural network-based method for spotting irregularities in a communication channel. NCS encountered uncertainty as a result of packet loss and time delays. Furthermore, the authors of [41], [42] offered a comparative analysis method that contrasted the reference trajectory's performance between a traditional proportional integral controller and a neural network-based controller when the system parameters were changing. Back-stepping was used to create a controller for a nonlinear networked system. Several fuzzy logic techniques are proposed to address this problem, and a nonlinear function prediction is made. Using an auxiliary signal, one can determine the input delay in accordance with the previously stated strategy. The stability problem brought on by packet loss and delay is resolved by using a switching controller. In order to present sufficient conditions of stability, the cone-complementarity-linearization (CCL) algorithm was also employed [43]. This article goes into further detail on designing H-infinity controllers for event-triggered NCS against quantization and denial-of-service attacks. Next, the time-varying Lyapunov functional method [44] was used to derive the necessary and sufficient conditions to guarantee the exponential stability of the NCS system in the presence of quantization and denial.

In a paper [45], a novel method for determining abnormalities caused by attacks that are particularly affected by packet losses and network delays was presented. The goal of this technique is to identify cyber-attacks directed towards communication networks. The suggested observer-centered approach employed the detection residual to recognize network attacks. The use of LMI-based techniques aids in the design of the observer gain matrix. Using an event-triggering methodology, the asymptotic stability of the networked system is discussed and the upper bound for network delay is also determined [46], [47]. The delta operator was utilized in paper [48] to address robust fault detection issues in NCS that included time-varying delay and packet dropout. The time delay is transformed using the Markovian jump system, which introduces parameter uncertainties into the system model.

The state feedback control gains and event triggered condition for NCSs with packet loss and brief network-induced delays are presented in this paper using a co-design approach. The system's exponential stability is ensured by the switched model upon which the design is based. Moreover, a condition that is self-triggered appears. Finally, a numerical example shows that the proposed method maintains system performance by lowering the control signal update frequency to a predefined value [49]. The paper [50] looked at the issue of fault detection in wireless NCS that is experiencing packet loss. The author also considers a model class with numerous delays and disruptions. Additionally, it is assumed that packet loss occurs in the controller-actuator relationship. The fault observer is represented as a switching discrete time linear system with time-delay, and the author used a Lyapunov approach to provide a sufficient condition [51].

By accounting for the NCS decay rate, the author computed the upper bound on packet loss and induced delay, thereby limiting the maximum overshoot of the control system. Additionally, a set of stability conditions was derived using Lyapunov-Krasovskii techniques [52]. The packet loss and delay problems of the distributed NCS were resolved by using the transmission technique known as event triggering. The controller was designed by the author to ensure that the subsystem was stable for the input signal. Determine the solution to the problem using the linear matrix inequality method and estimate the gain for bounded delay in order to make the system asymptotically stable. The authors in [53] simulated packet loss and networked delay brought on by NCS using Markov chains. It is assumed that the uncertainty of the system is either increasing or decreasing. To show how effective the used method is, a set of stability conditions was estimated using the Lyapunov function.

3. Problem Formulation

Figure 1 depicts the proposed networked control system. Following the collection of plant samples, the measured signal or data is transferred from the sensor to the control.

Depending on the communication medium, there could be various kinds of uncertainty in the information or measured signal. In order for the plant to operate as intended, the controller section computes the desired signal and sends it to the actuator via a communication channel.

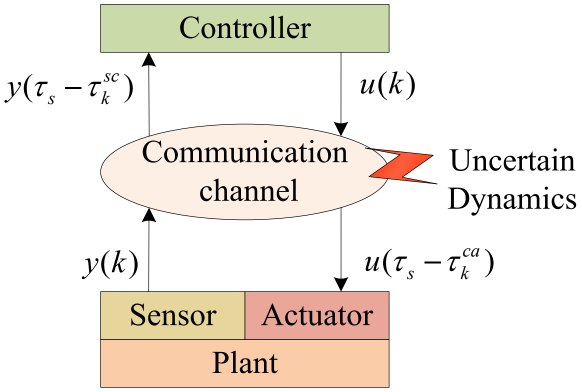

Fig. 1. Networked control system with uncertain dynamics

A. Plant Description

The linear time-invariant discrete system dynamics with disturbance are described as follows [29]:

$$x_{(k+1)} = Ax_{(k)} + Bu_{(k)} + \varphi_{(k)} \tag{1}$$

$$y_{(k)} = Cx_{(k)} + \omega_{(k)} \tag{2}$$

The A, B, C are matrices with the proper dimensions and the state-vector $x_{(k)}$, measurement signal $y_{(k)}$, control-vector $u_{(k)}$, and process Gaussian noise "$\omega_{(k)}$" and measurement Gaussian white noise "$\varphi_{(k)}$" with zero mean and covariance, Q and R, respectively, are the two types of noise.

It is assumed to satisfy the controllability "(A, B)" and observability "(A, C)".

4. Result Analysis

In order to observe the suggested methodology, a numerical problem with simulation results is presented in this section. The addition of an additional control action demonstrates the effectiveness of the methodology. The following equations, which are explained below, provide the plant dynamics in this numerical problem.

Plant dynamics is given as:

$$G = \frac{2}{(s+2)} \tag{3}$$

The different compensator is designed using proposed methodology. The simulation is run in the MATLAB Simulink environment. Figures 2 through 5 show the different simulated performance outcomes. The simulation results shown in Figure 2 show how the response signal tracks the input signal even in the presence of a communication channel disturbance. The step response is evaluated using compensator design 1.

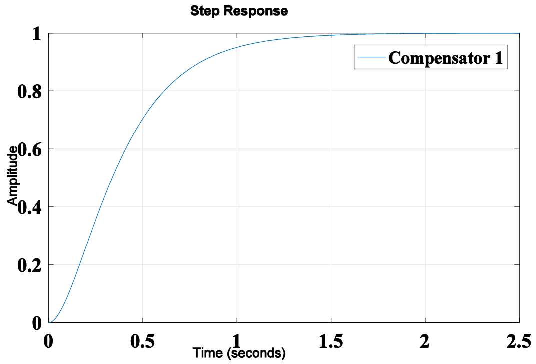

Fig. 2. Amplitude/Response with compensator design 1

The response signal with compensator design 2 in NCS with disturbance are shown in Figure 3. This proves that the recommended methodology is effective and response tracks step signal without overshoot.

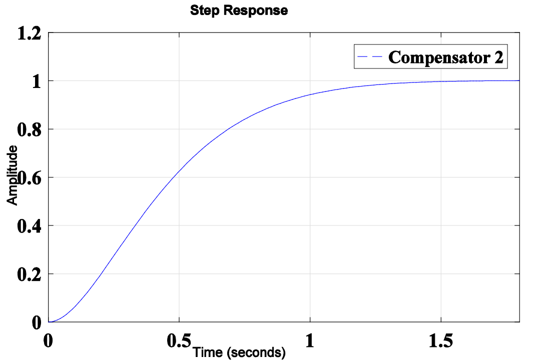

Fig. 3. Amplitude/Response with compensator design 2

The response signal with compensator design 3 in NCS with disturbance are shown in Figure 4. The response tracks step signal without overshoot and improved rise time.

Further improved design is presented with compensator design 4 in NCS with disturbance as shown in Figure 5. The response tracks step signal without overshoot and improved rise time.

The comparative analysis of various parameter with different compensator design is shown in Table 1.

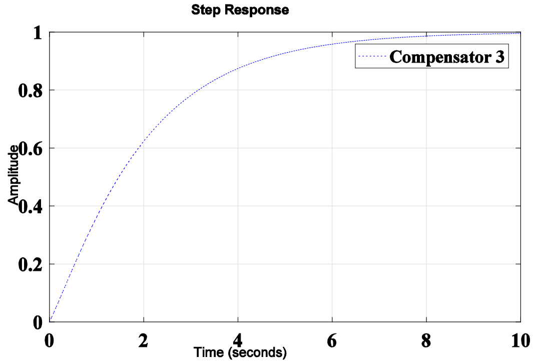

Fig. 4. Amplitude/Response with compensator design 3

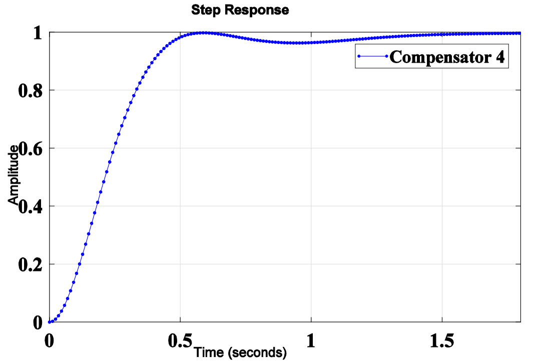

Fig. 5. Amplitude/Response with compensator design 4

Table 1
Comparative analysis of various parameter with different compensator design

Parameters	Rise Time	Settling Time	Overshoot	Peak Time
Compensator 1	0.7028	1.2441	0	2.8269
Compensator 2	0.7391	1.2200	0.0743	1.9687
Compensator 3	4.1476	7.3354	0	13.8727
Compensator 4	0.3186	1.2466	0	2.0596

5. Conclusion and Future work

The networked control system's stability and transient performance are crucial because adding an uncertain parameter makes the system more unstable and performs worse. Thus, the analysis of NCS system performance under ambiguous conditions, such as disturbance, is the main focus of this paper. The performance of NCS is demonstrated with control action and some appropriate stability conditions. The suggested methodology is used to design the different compensator. The MATLAB Simulink environment is used to run the simulation. The various results of the simulated performance are displayed in Figures 2 through 5. Figure 2's simulation results demonstrate how, even in the face of a communication channel disruption, the response signal follows the input signal. Compensator design 1 is used to evaluate the step response.

In NCS with disturbance, the response signal with compensator design 2 is displayed in Figure 3. This demonstrates that the suggested methodology works well and that the response tracks the step signal without going overboard.

Figure 4 displays the response signal in NCS with disturbance using compensator design 3. With better rise time and no overshoot, the response tracks the step signal. Figure 5 illustrates the compensator design 4 in NCS with disturbance, which presents an even better design. With better rise time and no overshoot, the response tracks the step signal.

Further research endeavors will focus on enhancing the control scheme and augmenting the nonlinear NCS's transient performance when confronted with uncertainty.

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